An ASAE Meeting Presentation

Paper Number: 052197

Nutrient Enrichment and Stream Periphyton Growth in the Southern Coastal Plain of Georgia

Richard Carey[1], George Vellidis[2], Richard Lowrance[3], Catherine Pringle[1]

[1]University of Georgia, Institute of Ecology, Athens, GA, 30602-2202, rcarey@uga.edu

[2]University of Georgia, Biological & Agricultural Engineering Department, Tifton, GA, 31793-0748

[3]Southeast Watershed Research Laboratory, USDA-ARS, Tifton, GA, 31793-0946

Written for presentation at the
2005 ASAE Annual International Meeting
Sponsored by ASAE
Tampa Convention Center
Tampa, Florida
17 - 20 July 2005

Abstract. *Blackwater rivers are common throughout the Atlantic coastal plain and water quality is heavily influenced by the flat topography, sandy soils and floodplain swamp forests. In the southern coastal plain of Georgia, streams regularly violate dissolved oxygen (DO) standards established by the Georgia Department of Natural Resources. Total Maximum Daily Load (TMDL) management plans must be developed for watersheds that are drained by DO-impaired streams but previous studies suggest DO may be naturally low. At nine sites throughout the region, eighteen passive nutrient diffusion periphytometers were deployed to determine if algal growth was nutrient and/or light limited. Periphyton biomass for treatments in the sun, measured as chlorophyll a, was significantly ($p < 0.05$) greater than corresponding treatments in the shade and algal growth was nutrient-limited at several sites where DO concentrations were well below regulatory standards. Factors other than algae may be responsible for low DO concentrations during summer.*

Keywords. Algae, Periphyton, Periphytometer, Dissolved Oxygen, Nutrient Enrichment, Water Quality

Introduction

Dark colored, low-gradient rivers in the southeastern United States that originate in swamps, bogs and marshes or contain instream swamps are called blackwater rivers (Smock and Gilinsky 1992). Elevated levels of dissolved organic matter (DOM) in these rivers, which are common throughout the lower Atlantic coastal plain, cause deep water to appear black (Wharton 1978). Dissolved organic acids originate from humic and fulvic acids leached from swamp soils that do not retain DOM leached from terrestrial vegetation (Beck et al. 1974; Meyer 1990) as well as decomposing litterfall from heavily vegetated floodplains and riparian zones. Water chemistry is also heavily influenced by the flat topography and typically sandy soils (Smock and Gilinsky 1992).

In the southern coastal plain of Georgia, the tributaries of the main blackwater river systems (Ochlockonee, Satilla, St. Mary's and Suwannee) regularly violate Georgia Department of Natural Resources dissolved oxygen (DO) standards. Section 303(d) of the Clean Water Act requires states to list impaired waters and establish Total Maximum Daily Load (TMDL) water quality management plans for watersheds that are drained by impaired streams. On Georgia's 2003 303(d) list, 91% of all coastal plain streams listed violated DO standards. Nutrient enrichment from nonpoint source (NPS) pollution is generally attributed as the reason for low DO. In one watershed, simulation models have suggested that a 40% average reduction in total nitrogen (N) and phosphorus (P) loads would be needed to bring the river back into compliance (GEPD 2000). But, recent research in Georgia and Louisiana indicates that low DO may be a natural condition for summer months in coastal plain watersheds (Vellidis et al., 2003; Ice and Sugden, 2003; Bosch et al., 2002). In light of these findings, nutrient load reductions may not improve DO concentrations in these streams if natural factors are primarily responsible for low DO.

Measuring nutrient enrichment

As nutrient loads increase, primary producers within aquatic ecosystems are the first to respond and a general paradigm is that P usually limits algal and aquatic plant growth in freshwater systems while N limitation is common in marine systems (Hecky and Kilham 1988; Correll 1998). Theoretical N:P molar ratios below 16:1 would lead to N limitation (Redfield 1958) but Allan (1995) noted that the shift from P to N limitation may actually occur anywhere from 10:1 - 30:1. Evidence also suggests co-limitation of P and N for algae and vascular plants in freshwater systems (Rabalais 2002). Algal yields in some nutrient amendment studies have been higher for both nutrients together than for either P or N enrichment alone (Smith et al. 1999; Tank and Dodds 2003). Dissolved inorganic nitrogen (DIN: NO_2 + NO_3 + NH_4) concentrations below 100 µg L^{-1} may limit algal growth but streams with values above 400 µg L^{-1} are unlikely to be nitrogen limited (Horne and Goldman 1994). For soluble reactive phosphorus, several studies have reported nutrient saturation threshold levels between 3 and 25 µg L^{-1} (Bothwell 1985; Rosemond et al. 2002; Horner et al. 1983).

Artificial nutrient diffusing substrates – clay pots, tiles and mesh in combination with nutrient-enriched agar solutions – are commonly used to determine limiting nutrients for attached algae or periphyton (Fairchild et al. 1985; Pringle et al. 1986; Corkum 1996; Mosisch et al. 2001; Tank and Dodds 2003). However, algal extraction (e.g. scraping) usually results in sample loss that may increase treatment variability and reduce the likelihood of detecting significant differences (Morin and Cattaneo 1992). In an alternative method that enabled complete recovery of attached algal assemblages, Matlock et al. (1998) determined the limiting nutrient in an Oklahoma stream with a quantitative nutrient enrichment periphytometer.

In this study, we used passive nutrient diffusion periphytometers modified from the design presented by Matlock et al. (1998) to investigate algal periphyton response to nutrient enrichment in Georgia's heavily shaded coastal plain streams. Our objective was to determine if nutrients and/or light are factors limiting algal growth in these streams. This study is a key step in understanding the dynamics of dissolved oxygen in blackwater coastal plain streams.

Methods

Periphytometers

The passive nutrient diffusion periphytometer developed by Matlock et al. (1998) consisted of a floating frame which supported twenty-four 1 L bottles containing nutrient solutions or deionized water. Holes were drilled in the bottle cap and both a membrane filter and a glass fiber filter were placed in the hole. The glass fiber filters functioned as an artificial growth substrate for periphyton while the membrane filter regulated diffusion of nutrient solutions from within the bottle. The glass fiber filter and membrane filter provided "a quiescent zone for passive diffusion of nutrients from the reservoir through the growth media to the stream" (Matlock et al. 1998). If the ambient stream water was nutrient limited, periphyton would preferentially colonize the filters on the nutrient bottles. If a stream was not nutrient limited, then periphyton growth would be similar on nutrient solution and control filters.

The experimental methods and periphytometer design used in this study were modified from those presented by Matlock et al. (1998) to address local conditions and were perfected after three months of development and testing during the summer of 2003. The main design change was that the periphytometers were miniaturized to operate in shallow, low-flow conditions typical of many coastal plain streams during the summer period. The performance of our periphytometer design under controlled conditions was also carefully evaluated.

Periphytometer Design

Each periphytometer consisted of a primary and secondary frame. Primary frames were constructed with lawn fence wire (7.6 cm by 5 cm grid) attached by plastic ties to 5 cm diameter schedule 40 PVC pipe as shown in Figure 1. The frames were 132 cm long and 58 cm wide. The V-shaped bow turned the device into the flow.

Forty 20 mL scintillation vials were attached by plastic ties to the wire grid in a completely randomized design because preliminary experiments revealed treatment proximity did not affect chlorophyll *a* results. There were ten replicates within each of the following groups:

1. Control - deionized water
2. Nitrate - 87.5 mg L^{-1} NO_3-N (using 632 mg L^{-1} KNO_3)
3. Phosphate - 12 mg L^{-1} PO_4-P (using 103.8 mg L^{-1} $Na_2HPO_4 \cdot 7H_2O$)
4. Nitrate + Phosphate

Vial caps were drilled to produce 1.6 cm holes and both a membrane filter (25 mm diameter, 0.45 µm pore size, Millipore catalog no. HVLP02500) and a glass fiber filter (1.5 µm pore size, Whatman 934-AH catalog no. 1827-105) were placed across the top of each vial. Glass fiber filters functioned as artificial growth substrates for periphyton while membrane filters regulated diffusion of nutrient solutions.

Our preliminary experiments showed that the glass fiber filter used as growth substrates were damaged by grazers unless protected. Attempts to protect the filters by wrapping screen over the filters were not successful because periphyton colonized both the screen and the filter and much of the algae was lost when the screen was removed. In the end, secondary frames with the same dimensions as the primary frames were constructed from 3.8 cm diameter schedule 40 PVC pipes. A fiberglass insect screen was taped to the bottom of the secondary frame and the entire secondary frame attached beneath the primary frames to protect the glass fiber filters from grazers and prevent floating debris from settling on top of the vials – thus potentially shading filters. High density foam weatherstrip (MD Building Products, 1.3 cm x 1.9 cm), glued along the top side of the secondary frame, closed the gap between primary and secondary frames when they were attached together. The fiberglass screen on each secondary frame was approximately 2.5 cm below vials of the primary frame. Several holes were drilled into each secondary frame to neutralize buoyancy. In this configuration, the 20 mL vials on primary frames were immediately beneath the water surface.

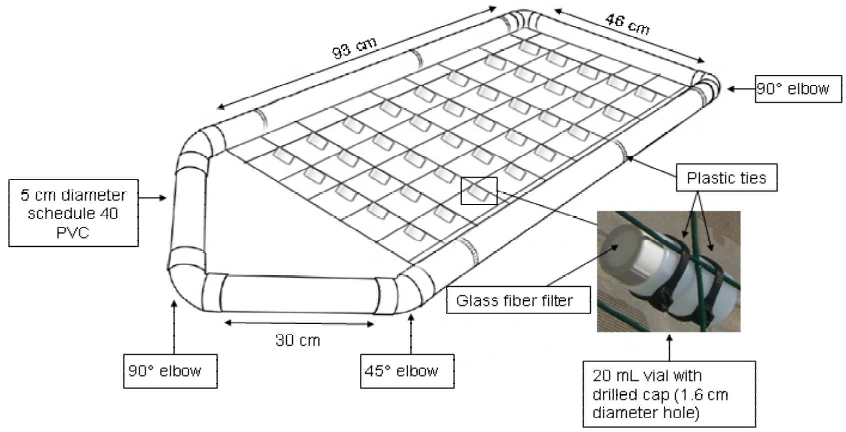


Figure 1. Periphytometer frame with forty 20 ml scintillation vials.

Periphytometers were prepared for deployment in a laboratory and transported to sites in a custom-built cooler. Each periphytometer was carefully placed in streams with the glass fiber filters parallel to stream flow. Metal rods attached to periphytometers with rope anchored the frames and allowed them to move with the current and adjust to fluctuating water levels (Figure 2).

Periphytometers were retrieved after fifteen days, placed in the cooler and transported to the laboratory. Glass fiber filters from each vial were then carefully removed, sorted by treatment groups in petri dishes, covered in foil and frozen for at least twenty-four hours. EPA Standard Method 10200H.3 was used to extract chlorophyll *a* from filters (APHA, 2000) and chlorophyll *a* content was determined by analysis on a Turner Designs TD 700 laboratory fluorometer. Values were expressed as mg m^{-2} by relating the mass of chlorophyll *a* extracted to the exposed surface area of glass fiber filters (1.7 cm^2).

Diffusion Rate

To investigate whether our periphytometer design supplied adequate nutrient concentrations to promote algal growth, we conducted a fifteen-day diffusion rate experiment. A 1.30 m long trough was built from 7.6 cm diameter schedule 40 PVC pipe (Figure 3). The 40 cm pipe was connected to a spigot that provided an artificial current (tap water) to the device with a flow velocity of 0.05 m s^{-1}. The pipe was supported at an angle by aluminum stands. Fifteen equally spaced scintillation vials were supported by wire and elastic bands in the flow.

Each vial was filled with the nitrate-phosphate solution and had drilled caps and filters as described previously. Vials were arranged 2.5 cm apart and one vial was removed after each day of the experiment and analyzed for residual nutrient concentrations – starting with the vial

Figure 2. Periphytometers deployed in Little Satilla Creek (Odum, GA).

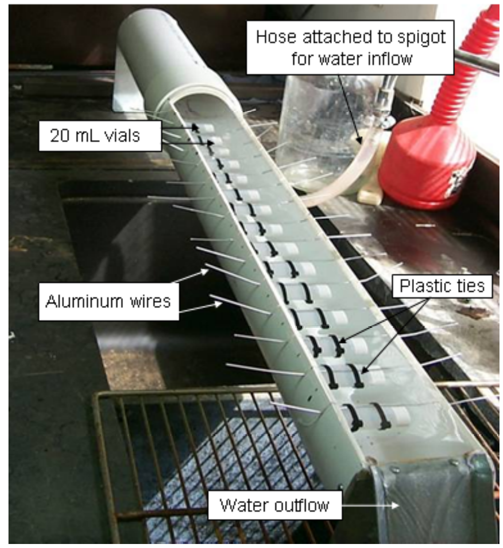


Figure 3. Apparatus for fifteen-day diffusion experiment.

farthest from the incoming water source. NO_3 and PO_4 concentrations within each individual glass fiber filter were also analyzed after vials were removed from the trough. Nutrient concentrations were extracted by homogenizing each filter in 10 mL of water and correcting for the water volume already present in the filters.

The NO_3 and PO_4 diffusion curves both produced similar exponential concentration declines in the vials but were always above nutrient saturation thresholds for algal growth. Vials had enough nutrients to continually enrich the glass fiber filters for fifteen days. Nutrient concentrations in the filters exposed to the nutrient solution were also sufficient to promote differential algal growth.

The diffusion experiment suggested that the periphytometer technique – with 20 mL nutrient reservoirs, membrane filters and glass fiber filters – could be used in nutrient enrichment studies. Algal growth on the glass fiber filters should not be hampered by nutrient availability. The 20 mL vials function as point sources of nutrients that enable deployed periphytometers to assess (1) whether algal growth in a stream is nutrient-limited and (2) what nutrient(s) is/are limiting.

Study sites

Eighteen passive nutrient diffusion periphytometers were deployed at nine sites between April and June, 2004. These sites were located within the Ocmulgee, Suwannee and Satilla river basins and were categorized as being within predominantly agricultural, predominantly forested, or mixed land use watersheds. We selected watersheds with three types of land use with the expectation that we would find decreasing nutrient gradients in the streams draining the watersheds as we went from agricultural to mixed use to forested watersheds.

Agricultural watersheds were dominated by a cotton – peanut crop rotation but generally contained mature hardwood riparian forest buffers. Agricultural land use was at least 40% of these watersheds. Forested watersheds consisted primarily of pine plantations managed for pulp and timber production in the uplands and hardwood forests in the flood plains (Figure 4).

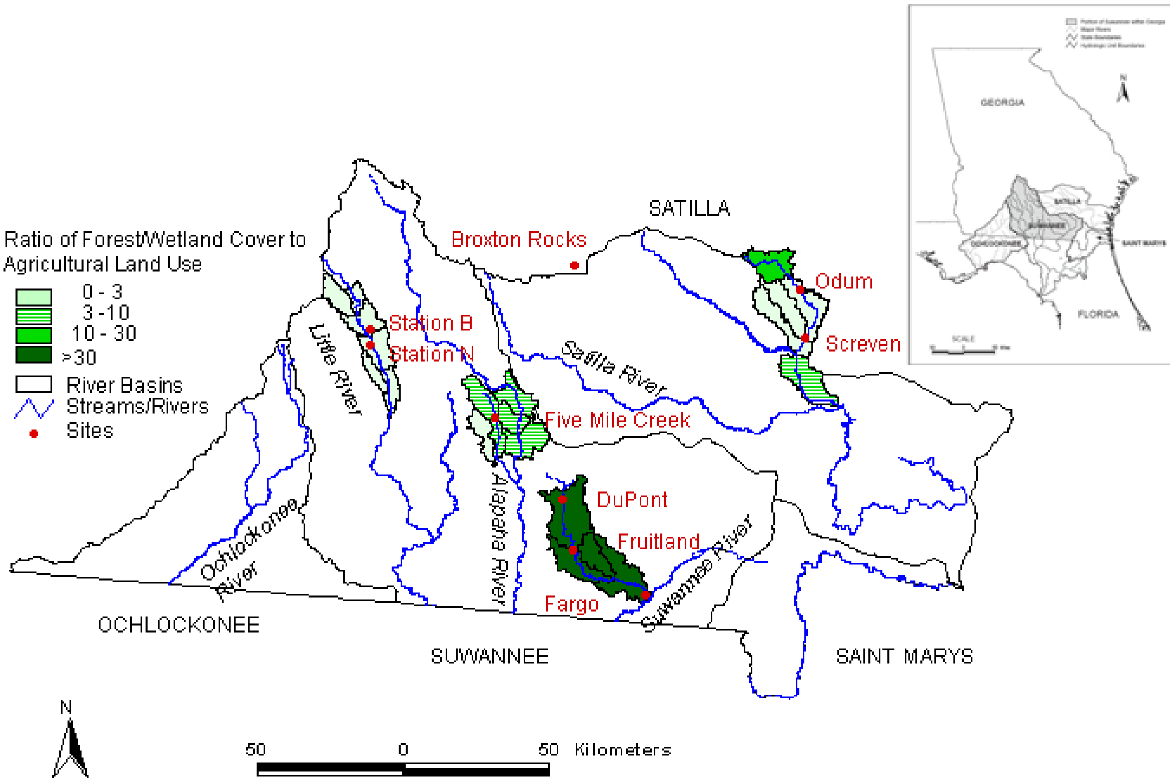


Figure 4. Study sites in Georgia's southern coastal plain.

With the exception of the Broxton Rocks Preserve, all study sites were on the public right-of-way where roads crossed the selected streams/rivers. Two periphytometers were deployed at each site, with one under tree canopy cover in the shade and the other in full sunlight.

Physicochemical and statistical analyses

Site water samples were collected on periphytometer deployment and retrieval dates. DO and temperature were measured with a YSI 550 DO meter and a LI-COR quantum sensor (LI-190SA) measured photosynthetically active radiation (PAR). Stream flow rates were below the threshold of our current velocity measurement instruments during the experiments. However, at two sites, USDA-ARS gaging Stations N and B in the Little River watershed, daily flow measurements were available and water samples were collected daily throughout periphytometer deployment. Stream water samples from all sites were analyzed for suspended solids, NO_3-N, NH_4-N, PO_4-P(soluble reactive phosphorus), chloride, potassium and dissolved organic carbon (DOC) using standard analytical techniques (APHA, 2000). A pH meter (Orion Model SA720) was used to measure water sample pH in the lab. Residual solutions in 20 mL vials were also analyzed for NO_3-N, and PO_4-P concentrations using standard techniques (APHA, 2000).

Stream water samples were compared using either an analysis of variance (ANOVA) or Kruskal-Wallis procedures in Statistical Analysis Systems (SAS Institute, Cary, NC). The ANOVA procedure was used when assumptions of normality and homoscedasticity could be met (raw data or log transformations). Linear regressions were used to determine whether residual treatment concentrations in 20 mL vials were significantly related to chlorophyll *a* values. For each treatment group ($NO_{3,}$ PO_4 and NO_3-PO_4), mean chlorophyll *a* values from each site in the shade and sun were compared to corresponding mean residual nutrient concentrations. Chlorophyll *a* treatment means, for individual periphytometers, were compared using an ANOVA (where necessary, values were log transformed). T-tests were also used to compare treatment means in the shade at each site to their corresponding groups in the sun. Tukey's multiple comparison procedure was used to determine which means were significantly different at $\alpha = 0.05$.

Results

Site variables

DO concentrations were below regulatory standards at several sites. Little River (Station B) and Little Satilla Creek (Screven and Odum) all had DO concentrations below 1.00 mg L^{-1} on both deployment and retrieval dates. Stream temperatures ranged between 15 - 24°C and except for Odum, where trees were cut during the experiment, PAR values in the shade were below 100 µmol $s^{-1}m^{-2}$ but generally above 1000 µmol s^{-1} m^{-2} in the sun. Average stream pH values at Station N (6.80) and Station B (6.95) were significantly greater ($p < 0.01$) than all other sites while Fruitland (4.10) and Fargo (4.07) had significantly lower ($p < 0.01$) pH values than every site except Five Mile Creek at Weber (4.23).

Except for DuPont and Station N, NO_3-N concentrations on deployment and retrieval dates were below 45 µg L^{-1}. Station N (112 µg L^{-1}) had the highest NO_3-N concentrations while Broxton Rocks (17 µg L^{-1}) had the lowest. The lowest PO_4 –P concentrations were measured at Station B (7 µg L^{-1}) which drained an agricultural watershed while the highest concentrations were measured at Screven (53 µg L^{-1}) and Odum (35 µg L^{-1}) which were in a mixed land use watershed. NH_4-N concentrations at DuPont (289 µg L^{-1}), Fargo (389 µg L^{-1}) and Screven (576 µg L^{-1}) were much higher than the other sites. DOC levels at Fruitland (55.46 mg L^{-1}) and Fargo (52.22 mg L^{-1}) were much greater than all other study sites. Station B (14.93 mg L^{-1}), Broxton Rocks (18.57 mg L^{-1}) and Station N (13.76 mg L^{-1}) had significantly lower DOC concentrations than all other sites. A summary of site variables is given in Figures 5a and 5b. A statistical analysis of site variable differences is given in Carey (2005).

Chlorophyll a Analyses

Treatments in the shade were significantly different at only three sites: Broxton Rocks, Station B and Odum. Mean chlorophyll *a* values for treatments in the sun were significantly greater than their corresponding groups in the shade at all sites except for NO_3 treatment groups at Broxton Rocks. Periphytometers were deployed at this site in early spring before the trees in the shaded areas had developed a full leaf canopy.

For both periphytometers at Broxton Rocks, algal growth was primarily limited by P and secondarily limited by N (Figures 5a and 5b). At Station B, PO_4 filters in the shade were significantly greater ($p < 0.05$) than control and NO_3 filters. Chlorophyll *a* values in the shade at both Stations N and B were the lowest in the study. Station B and Five Mile Creek were co-limited by both N and P in the sun. Algal growth in the shade at Odum was co-limited by both nutrients but in the sun, algae was primarily limited by N and secondarily limited by P. Fruitland was P limited and no treatment group was significantly greater than controls at DuPont, Fargo or Screven (Figures 5a and 5b).

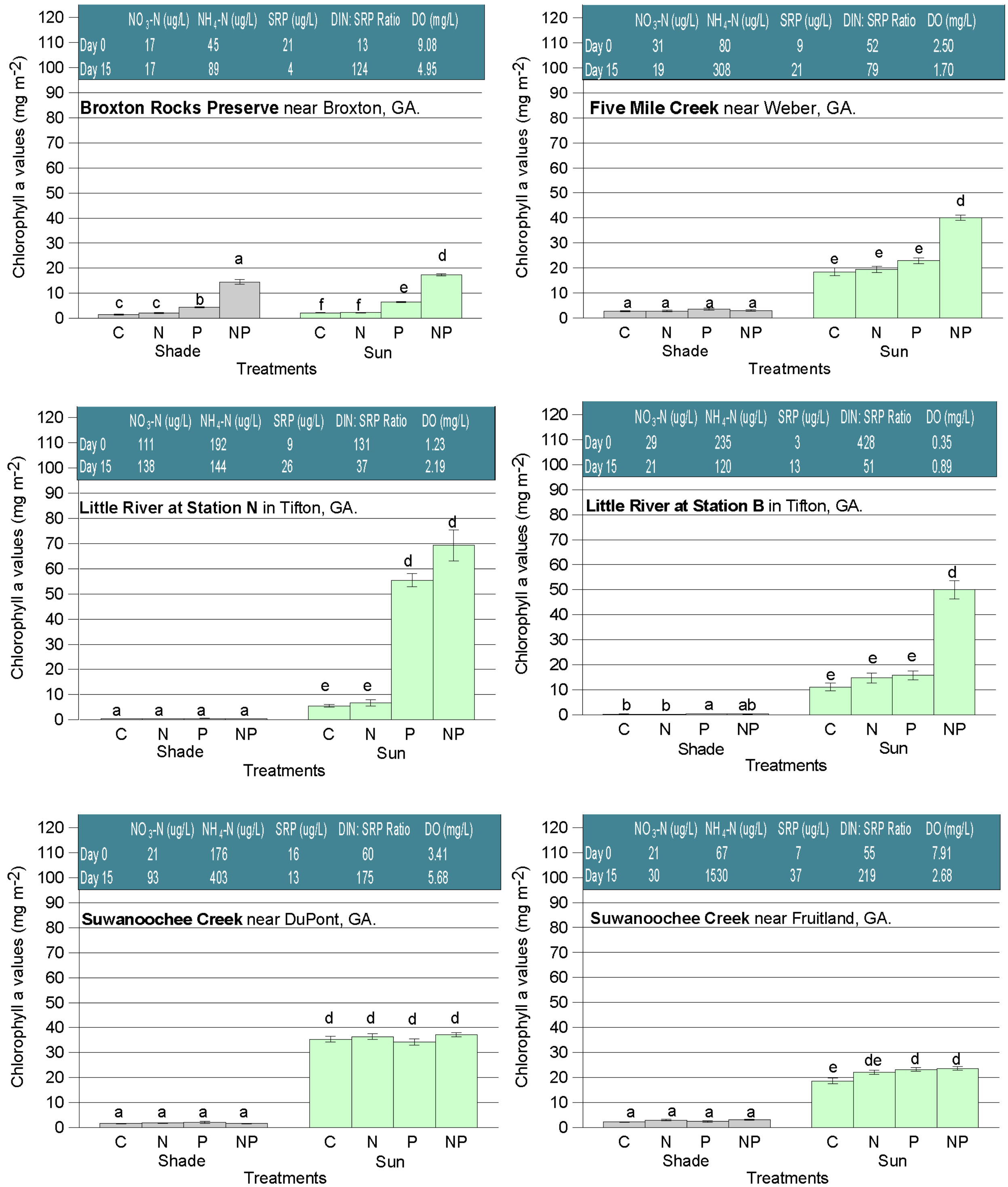
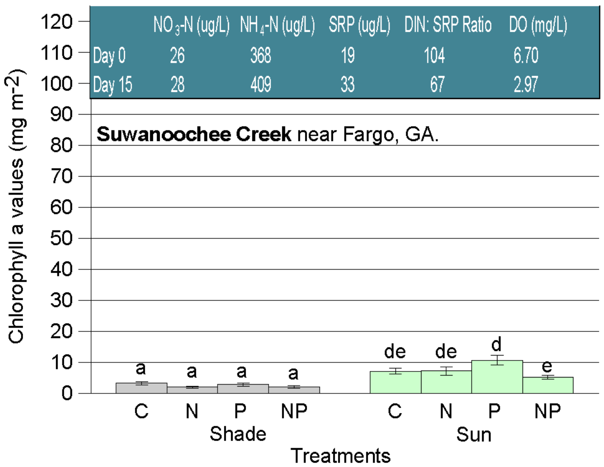
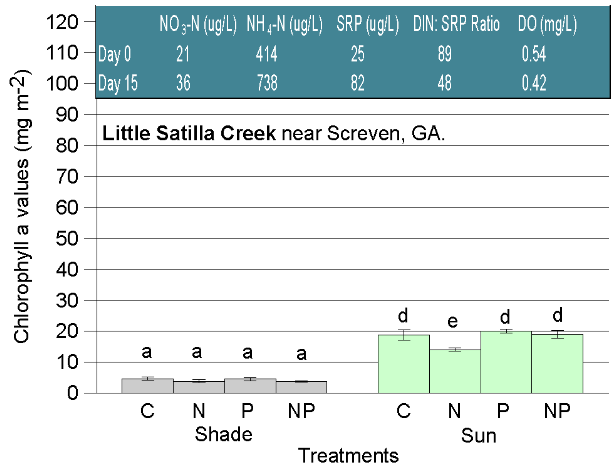


Figure 5a. Ambient stream nutrient concentrations and summary chlorophyll *a* data for the nine study sites. Different letters within each category (shade or sun) represent treatment means that are significantly different (Tukey's test, $p < 0.05$) and error bars represent standard error.





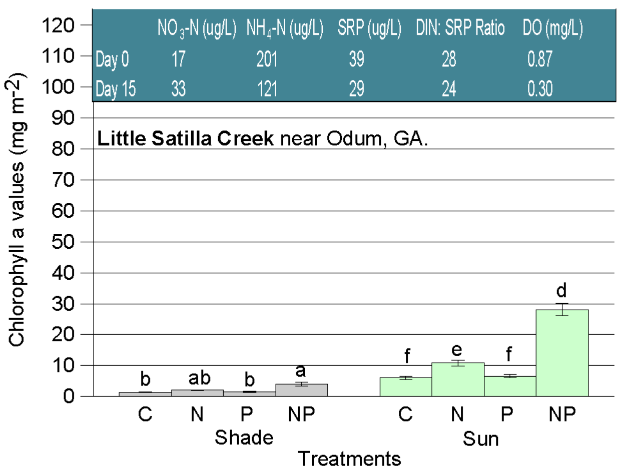


Figure 5b. Ambient stream nutrient concentrations and summary chlorophyll *a* data for the nine study sites. Different letters within each category (shade or sun) represent treatment means that are significantly different (Tukey's test, $p < 0.05$) and error bars represent standard error.

Discussion

Light Availability

Light conditions clearly affected chlorophyll *a* production. Because chlorophyll *a* levels for both treatments and controls were significantly greater in the sun, periphyton growth may be predominately light-limited in heavily shaded coastal plain streams. Light is "a prerequisite for a phototrophic existence" because it enables periphyton to utilize inorganic compounds (Hill 1996). Nutrients and irradiance are critical factors affecting primary productivity but nutrient limitation of algal growth generally occurs only above photo-saturation levels (Mosisch et al. 1999). Algal biomass in some streams can therefore be primarily limited by irradiance and secondarily limited by nutrients (Lowe et al. 1986; Rosemond 1994). Experiments at both Broxton Rocks and Little Satilla Creek near Odum further demonstrated the relative importance of light. Periphytometers in the shade at Broxton Rocks (incomplete canopy cover because it was early Spring) and Odum (trees cut) were unintentionally exposed to higher irradiance levels and resultant chlorophyll *a* values reflected patterns observed in the sun.

DOC concentrations and total suspended solids (TSS) may also inhibit periphyton growth because of light attenuation. Riparian canopy cover can intercept up to 95% of the incident solar radiation in narrow stream channels and as light penetrates the water, high DOC concentrations and suspended solids can scatter and absorb light (Hill 1996). Smock and Gilinsky (1992) noted that DOC in blackwater streams can approach 50 mg L^{-1} while concentrations greater than 3 mg L^{-1} are rarely found in higher-gradient southeastern streams. Highest DOC concentrations in this study were found in Suwannoochee Creek, as all three sites (DuPont, Fruitland and Fargo) had values that approached or exceeded 50 mg L^{-1}.

Periphyton Response to Nutrient Enrichment

Periphyton biomass accrual during the study was similar to results from previously published nutrient diffusing substrata (NDS) experiments. When the original periphytometer technique was used (Matlock et al. 1998; Matlock et al. 1999a; Matlock et al. 1999b), mean chlorophyll *a* values after two weeks were between 2.10 and 62.20 mg m^{-2}. Tank and Dodds (2003) used glass fiber filters, 60 mL plastic containers and agar nutrient solutions to investigate nutrient limited algal growth in ten streams across the U.S. and obtained chlorophyll *a* values between 1.00 and 132.00 mg m^{-2} after three weeks. In Canada, Corkum (1996) compared algal growth in forested and agricultural rivers using agar nutrient solutions as well and after five-six weeks, chlorophyll *a* values ranged from 2.00 to 95.00 mg m^{-2}.

Periphytometer results suggested ambient stream nutrient concentrations were below requirements for algal species at Broxton Rocks, Little River at Stations N and B, Five Mile Creek near Weber, Suwannoochee Creek near Fruitland (Figure 5a), and Little Satilla Creek near Odum (Figure 5b). At Station B for example, the literature indicates that average DIN (152 µg L^{-1}) and SRP (7 µg L^{-1}) concentrations could be below algal saturation levels (Horne and Goldman 1994; Horner et al. 1983).

For all sites except Little Satilla Creek near Odum, stream DIN: SRP molar ratios on periphytometer deployment and retrieval dates suggested P-limited algal growth. Nutrient ratios at Odum, the only site that was N limited, were between 24:1 and 28:1. Odum was primarily limited by N but NO_3-PO_4 enriched filters produced the greatest periphyton biomass and this was consistent with other published NDS experiments.

While Screven was characterized as mixed agricultural/forested watershed, both DuPont and Fargo were located in predominantly forested watersheds and algal growth was not nutrient limited at any of the three sites. Chlorophyll *a* results at Screven reflected the saturated nutrient environment and the especially high chlorophyll *a* values for control (35.00 mg m^{-2}) filters at DuPont suggested the nutrient environment here was also saturated.

Periphyton growth at Fruitland was nutrient limited in the sun but treatment means were similar (Figure 5a). Stream DIN: SRP molar ratios (55 – 219) suggested P-limited algal growth. Mean chlorophyll *a* values from PO_4 (23.20 mg m^{-2}) and NO_3-PO_4 (23.60 mg m^{-2}) filters that were significantly greater ($p < 0.01$) than controls (18.70 mg m^{-2}) support this finding. But because NO_3 (22.10 mg m^{-2}) filters were not significantly different ($p > 0.05$) from any other treatment group, results from this experiment are unclear.

Morin and Cattaneo (1992) analyzed several periphyton field studies and found that sampling designs used would only detect significant differences ($\alpha = 0.05$) in periphyton productivity if treatment means differed by at least a factor of two. Periphytometer results from Broxton Rocks, Station N, Station B, Five Mile Creek and Odum generally supported this analysis. Throughout our study however, low within-treatment variability for chlorophyll *a* values suggested smaller differences could be detected and this was indeed evident at both Fruitland and Screven. This low within-treatment variability for chlorophyll *a* values also indicates that our technique for measuring nutrient enrichment is quite powerful.

Conclusions

Implications for Georgia Coastal Plain Streams

Within blackwater streams in the southern coastal plain of Georgia, multiple factors likely reduce the possibility of explosive algal growth. For example, since most coastal plain streams are shaded and shade is a limiting factor for algal growth even in nutrient-rich conditions, nutrient enrichment is unlikely to result in excessive algal growth. In streams with dense algal populations, algae can have a significant effect on DO.

Additionally, for sites with both low DO concentrations and nutrient deficiencies (Broxton Rocks, Five Mile Creek near Weber, Suwannoochee Creek near Fruitland, Little Satilla Creek near Odum and Little River at Stations N and B), prevailing conditions were not conducive to optimal algal growth. The potential for algae to significantly lower DO concentrations should be greatest when algae are experiencing optimal growth conditions.

Results from experiments at Stations N and B also demonstrated that benthic algae can be susceptible to seasonally low flows in southeastern blackwater streams. Both sites were located in nutrient-replete agricultural areas where critical factors such as irradiance, not nutrient deficiencies, would be expected to limit algal growth. However, minimal flow during periphytometer experiments reduced the supply of nutrients and algal growth *was* nutrient limited. Both Stations N and B had extremely low DO concentrations yet the actual nutrient environment for benthic algae was poor.

Limitations and Recommendations

Since we have low DO in streams where algae are nutrient-limited, our results suggest factors other than algae are responsible for seasonally low DO concentrations. However, our study has several limitations. First, specific algal taxa were not identified and comparisons across sites may have yielded information about the physiological requirements for algae in Georgia coastal plain streams. Additionally, stream water samples were only collected on periphytometer deployment and retrieval dates (except at Stations N and B). Many experiments were conducted simultaneously at remote sites and it was not possible to collect daily stream water samples. Daily flow measurements at all sites would have also increased the utility of flow data from Stations N and B because comparisons – periphyton growth, residual and stream nutrient concentrations etc. – could be made across all sites.

Future research projects that explore the significance of other potential variables (e.g. sediment oxygen demand), and specifically addressed the effect of algae on DO levels, would be helpful in eliminating algae as the cause of low DO in coastal plain streams. Results from such projects could therefore lead to the eventual removal of coastal plain streams from Georgia's 303(d) list because the natural range of DO concentrations may be lower than current standards.

Acknowledgements

Thanks to Chris Clegg and Leila Hargett at the USDA-ARS Southeast Watershed Research Laboratory and Paige Gay, Debbie Coker, Wynn Bloodworth, and Andy Knowlton at the University of Georgia's National Environmentally Sound Production Agriculture Laboratory for their advice and assistance throughout this project. This research was funded by a grant from the USDA-CSREES Integrated Research, Extension, and Education Program and by Hatch and State funds allocated to the Georgia Agricultural Experiment Stations.

References

Allan, J.D. 1995. Stream Ecology: Structure and function of running waters. Chapman and Hall, New York, New York, USA.

American Public Health Association (APHA). 2000. Standard methods for the examination of water and wastewater. American Public Health Association, Washington D.C., USA.

Beck, K.C., J.H. Reuter and E.M. Perdue. 1974. Organic and inorganic geochemistry of some coastal plain rivers of the southeastern U.S. Geochimica Cosmochimica Acta 38:341-364.

Bosch, D., R. Lowrance. G. Vellidis. 2002. Dissolved oxygen concentrations in three coastal plain watersheds: Implications for TMDLs In A. Saleh (ed) *Proceedings of the Total Maximum Daily Load (TMDL) Environmental Regulations Conference,* pp. 606-610. ASAE, St. Joseph, Michigan.

Bothwell, M.L. 1985. Phosphorus limitation of lotic periphyton growth rates: an intersite comparison using continuous-flow troughs (Thompson River system, British Columbia). Limnology and Oceanography 30: 527-542.

Carey, R.O. 2005. The effect of nutrient enrichment on stream periphyton growth in the southern coastal plain of Georgia: Implications for low dissolved oxygen. MS thesis. Athens, Georgia: University of Georgia, Institute of Ecology.

Corkum, L.D. 1996. Responses of chlorophyll-a organic matter, and macroinvertebrates to nutrient additions in rivers flowing through agricultural and forested land. Archiv fur Hydrobiologie 136: 391-411.

Correll, D.L.1998. The role of phosphorus in the eutrophication of receiving waters: A Review. Journal of Environmental Quality 27:261-266.

Fairchild, G.W., R.L. Lowe and W.B. Richardson. 1985. Algal periphyton growth on nutrient-diffusing substrates: an in situ bioassay. Ecology 66(2):465-472.

Francoeur, S.N. 2001. Meta-analysis of lotic nutrient amendment experiments: detecting and quantifying subtle responses. Journal of the North American Benthological Society 20: 358-368.

Georgia Department of Natural Resources – Environmental Protection Division. 2000. Georgia Department of Natural Resources. Atlanta, GA.

Hecky, R.E. and P. Kilham. 1988. Nutrient limitation of phytoplankton in freshwater and marine environments: A review of recent evidence on the effects of enrichment. Limnology and Oceanography 33:796-822.

Hill, W. 1996. Effects of light. Pages 121-144 *in* Stevenson, R.J., Bothwell, M.L., Lowe, R.L., editors. Algal Ecology: Freshwater Benthic Ecosystems. Academic Press, San Diego, California, USA.

Horne, A.J. and Goldman, C.R. 1994. Limnology. McGraw-Hill, New York, New York, USA.

Horner, R.R., E. B. Welch and R.B. Veenstra. 1983. Development of nuisance periphytic algae in laboratory streams in relation to enrichment and velocity. Pages 121-131 *in* R.G. Wetzel, editor. Periphyton of Freshwater Ecosystems. Dr. W. Junk Publishers, The Hague, The Netherlands.

Ice, G., and B. Sugden. 2003. Summer dissolved oxygen concentrations in forested streams of northern Louisiana. *Southern Journal of Applied Forestry* 27 (2): 92-99.

Lowe, R.L., S.W. Golladay and J.R. Webster. 1986. Periphyton response to nutrient manipulation in streams draining clearcut and forested watersheds. Journal of the North American Benthological Society 5:221-229.

Matlock, M.D., M.E. Matlock, D.E. Storm, M.D. Smolen, and W.J. Henley. 1998. Limiting nutrient determination in lotic ecosystems using a quantitative nutrient enrichment periphytometer. Journal of the American Water Resources Association 34:1141-1147.

Matlock, M.D., D.E. Storm, M.D. Smolen and M.E. Matlock. 1999a. Determining the lotic ecosystem nutrient and trophic status of three streams in eastern Oklahoma over two seasons. Aquatic Ecosystem Health and Management 2: 115-127.

Matlock, M.D., D.E. Storm, M.D. Smolen, M.E. Matlock, A.M.S. McFarland and L.M. Hauck. 1999b. Development and application of a lotic ecosystem trophic status index. Transactions of the ASAE 42(3): 651-656.

Meyer, J.L. 1990. A blackwater perspective on riverine ecosystems: Ecologists are taking a broader view of streams and their food webs. BioScience 40:643-651.

Morin, A. and A. Cattaneo. 1992. Factors affecting sampling variability of freshwater periphyton and the power of periphyton studies. Canadian Journal of Fisheries and Aquatic Sciences 49: 1695-1703.

Mosisch, T.D., S.E. Bunn, P.M. Davies and C.J. Marshall. 1999. Effects of shade and nutrient manipulation on periphyton growth in a subtropical stream. Aquatic Botany 64:167-177.

Mosisch, T.D., S.E. Bunn and P.M. Davies. 2001. The relative importance of shading and nutrients on algal production in subtropical streams. Freshwater Biology 46: 1269-1278.

Pringle, C.M., P. Paaby-Hansen, P.D. Vaux and C.R. Goldman. 1986. In situ nutrient assays of periphyton growth in a lowland Costa Rican Stream. Hydrobiologia 134:207-213.

Rabalais, N. 2002. Nitrogen in aquatic ecosystems. Ambio 31:102-111.

Redfield, A.C. 1958. The biological control of chemical factors in the environment. American Scientist 46: 205-222.

Rosemond, A.D. 1994. Multiple factors limit seasonal variation in periphyton in a forest stream. Journal of the North American Benthological Society 13:333-344.

Rosemond, A.D., C.M. Pringle, A. Ramirez, M.J. Paul and J.L. Meyer. 2002. Landscape variation in phosphorus concentration and effects on detritus-based tropical streams. Limnology and Oceanography 47: 278-289.

Smith, V.H., G.D. Tilman, and J.C. Nekola. 1999. Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. Environmental Pollution 100:179-196.

Smock, L.A., and E. Gilinsky. 1992. Coastal Plain blackwater streams. Pages 272-311 *in* C.T. Hackney, S.M. Adams, and W.H. Martin, editors. Biodiversity of the southeastern United States. John Wiley and Sons, New York, New York, USA.

Tank, J.L. and W.K. Dodds. 2003. Nutrient limitation of epilithic and epixylic biofilms in 10 North American streams. Freshwater Biology 48: 1031-1049.

Vellidis, G., R. Lowrance, M.C. Smith, S. Crow, and A. Milton. 2003. Establishing the natural range of dissolved oxygen in streams of the coastal plain of Georgia. In A. Saleh (ed) *Proceedings of the 2nd Conference on Watershed Management to Meet Emerging TMDL Regulations*, ASAE, St. Joseph, Michigan, p 414-419.

Wharton, C.H. 1978. The natural environments of Georgia. Georgia Department of Natural Resources, Atlanta, Georgia, USA.